EFFECT OF HIGH-PERFORMANCE ARTIFICIAL LIGHTWEIGHT AGGREGATE ON SEVERAL PROPERTIES OF LIGHTWEIGHT CONCRETE

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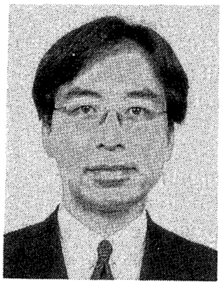
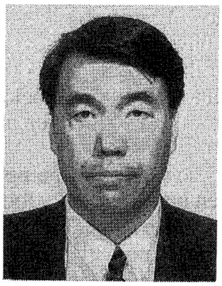


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A high-performance artificial lightweight aggregate has been developed through application of a new manufacturing method. In this study, we investigate the properties of this high-performance artificial lightweight aggregate, and examine the effects of this aggregate on several properties of the resulting lightweight concrete. The aggregate is principally characterized by aggregate particles with no cracks or large voids, and most of the pores are closed and uniformly small. The aggregate water absorption is so low that, even if dry aggregate is used, the concrete can be placed by pump without loss of workability. The strength of the aggregate is improved, so a high-strength concrete is obtained. Furthermore, it turns out that the resulting lightweight concrete has high resistance to freezing and thawing action, even when it suffers the high pressures imposed by pumping.

Keywords : *high-performance artificial lightweight aggregate, lightweight concrete, closed pores, low absorption characteristics, compressive strength, freezing and thawing durability*

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1. INTRODUCTION

Lightweight concrete is an effective way to reduce the size and weight of structural members in, for example, ultra-high-rise buildings and long-span structures. On the other hand, there are several unresolved technical problems in the use of lightweight concrete with artificial lightweight aggregate : porosity of the aggregate, little increase in compressive strength at the high-strength level, and high absorption by the aggregate. In particular, high absorption leads to very serious problems in casting the concrete, and to low resistance to freezing and thawing.

If lightweight concrete made with insufficiently prewetted aggregate is pumped, slump loss occurs, since the porous aggregate absorbs water during pumping. Frequent blockages may happen in the conveying pipe, and the concrete may not retain good enough workability for casting and placing. To overcome such problems, lightweight aggregate is usually made with a high absorption of 25 to 30 percent when it is to be pumped. This high absorption is realized by means of a prewetting or presoaking process. However, such lightweight concrete may be susceptible to deterioration due to freezing and thawing action when employed in a cold region. The authors have proposed several methods of manufacturing lightweight concrete with superior durability [1]. A synthetic evaluation of the proposed methods based on test results indicates that lightweight aggregate with a low absorption below 5 percent is ideal, though such concrete can be cast only by bucket, not by pump for the reason given above.

To improve both workability and durability so as to allow pumping, a new manufacturing method for high-performance lightweight aggregate has been investigated by focusing on the pore structure of the aggregate particles. Most lightweight aggregates on the market consist of expanded shale or expanded clay. Most of their pores are open, so they readily communicate with each other, and large voids and cracks are easily formed. The pores can be made mostly closed and uniformly small by changing both the raw materials and the manufacturing method.

We report here on a new aggregate manufacturing method, along with several properties of the aggregate and the effects of using this aggregate on several properties of lightweight concrete. In particular, we consider its effects on durability in the face of freezing and thawing.

2. MANUFACTURING METHOD FOR NEW LIGHTWEIGHT AGGREGATE

The raw material used for the high-performance artificial lightweight (HAL) aggregate is biotite rhyolite, which originates in lava. This material is produced on Niijima Island, off Tokyo. It features a high content of SiO_2 (78.7%), Al_2O_3 (12.3%), Na_2O (4.0%), K_2O (2.7%), and a low content of Fe_2O_3 (0.9%).

The aggregate is manufactured according to a new method, as shown in Fig. 1. This method is characterized by the pulverization of the raw material, the addition of a foaming agent, and a burning procedure. Very fine pulverization is achieved by using a ball mill, giving a particle size smaller than 10

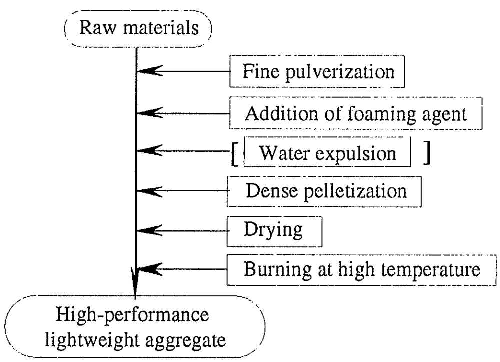


Fig. 1 Manufacturing process of high-performance lightweight aggregate

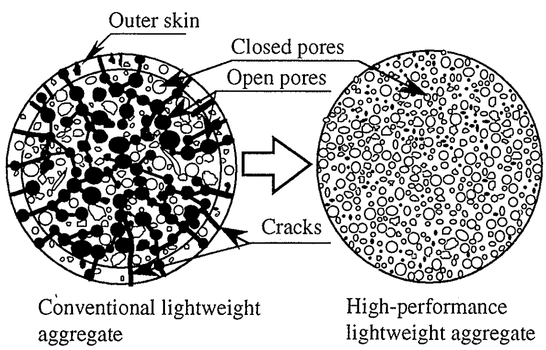


Fig. 2 Schematic pictures of pore structure in lightweight aggregate particles

Table 1 Materials used

Materials	Type		Properties or chemical composition
Cement	Normal portland cement	C	Specific gravity=3.16; Specific surface area (Blaine)=3250cm^2/g
Mineral admixture	Silica fume	SF	Specific gravity=2.21; Specific surface area (BET)=20.8m^2/g; SiO_2 =90.6%
Coarse aggregate	High-performance artificial lightweight aggregate	HAL-A	Gmax=15mm; Specific gravity (oven-dry)=0.92; 24h absorption=1.60%; Fineness modulus=6.50
		HAL-B	Gmax=15mm; Specific gravity (oven-dry)=1.22; 24h absorption=0.62%; Fineness modulus=6.50
		HAL-C	Gmax=15mm; Specific gravity (oven-dry)=1.66; 24h absorption=0.40%; Fineness modulus=6.50
	Conventional lightweight aggregate	AL-1	Gmax=15mm; Specific gravity (oven-dry)=1.31; 24h absorption=8.67%; Fineness modulus=6.30
		AL-2	Gmax=15mm; Specific gravity (oven-dry)=1.26; 24h absorption=9.94%; Fineness modulus=6.33
Fine aggregate	Land sand	S	Specific gravity (saturated surface-dry)=2.59; Absorption=1.50%; Fineness modulus=2.82
Chemical admixture	Superplasticizer		Polycarbonic acid ether
	AE agent		Anion surface active agent based upon alkyl-carboxylic acid compound

μm, and very dense pellets are made with suitable apparatus - such as a filter press. This shortens the mutual distance between powder particles and uniformly disperses the foaming agent. Furthermore, few micro cracks occur in the aggregate particles, because the size of the quartz crystals in the raw material is reduced. By controlling the burning temperature and the kiln atmosphere (oxidizing atmosphere), the biotite rhyolite itself becomes non-expansive, unlike expanded shale or clay. In order to induce the formation of pores, a reducing agent (SiC) is employed and acts as a foaming agent. This procedure results in the formation of closed and uniformly small pores, as illustrated in Fig. 2. The specific gravity of the aggregate can be varied over a wide range by adjusting the burning temperature and the quantity of foaming agent.

3. SCOPE OF TESTS

(1) Materials Used and Concrete Mixes

The materials used in this study are shown in Table 1. Normal portland cement and undensified silica fume were used as the cementitious binders. The fine aggregate was land sand. Three types of HAL (HAL-A, B, and C) and two types of lightweight aggregate (AL-1 and AL-2) were used as the coarse aggregate. The latter are readily available expanded shale aggregates. The HAL aggregates were manufactured, so as to be significantly lighter than conventional lightweight aggregates, with equivalent specific gravity to the conventional lightweight aggregate under oven-dry and sufficiently prewetted surface-dry conditions. The oven-dry specific gravity of the HAL aggregates was made 0.9±0.1 for HAL-A, 1.2±0.1 for HAL-B, and 1.6±0.1 for HAL-C aggregate by adjusting the degree of foaming. These values are equivalent to those of lightweight aggregates as specified by JIS A 5002 for L, M, and H grades, respectively. A superplasticizer and AE agent, the principal ingredients of which were polycarbonic acid ether and alkyl-carboxylic acid compound, were employed as chemical admixtures.

The concrete mix proportions are shown in Table 2. In order to make effective use of the high performance of this aggregate, the water-to-cementitious-binder ratios (W/(C+SF)) were made 21.9, 32.0, and 40.0 percent, respectively. Replacement of cement by silica fume (SF/(C+SF)) was 0 or 10 percent. HAL aggregates were used under saturated surface-dry conditions after absorption for more than 24 hours. The AL-1 aggregate was used under oven-dry or sufficiently prewetted surface-dry conditions. The aim was to obtain a slump of 18 to 24 cm, depending upon the mix proportion. Air content was measured by the pressure method in accordance with JIS A 1128, and the aim was an air content of 6 percent after mixing. Test results of slump, air content, and density are also shown in Table 2.

Table 2 Mix proportions and properties of fresh concrete

Mix proportions							Properties of fresh concrete		
Mixture name	Type of aggregate	Absorption of aggregate (%)	W/(C+SF) (%)	s / a (%)	SF/(C+SF) (%)	Unit quantity of water (kg/m^3)	Slump (cm)	Air (%)	Density (kg/m^3)
22AS	HAL-A	1.97	21.9	38	10	150	22.0	7.9	1701
32AS			32.0	41		160	20.0	6.9	1638
40AN			40.0	43	0		16.5	6.7	1634
22BS	HAL-B	0.45	21.9	38	10	150	17.5	4.7	1880
32BN			32.0	41	0	160	18.5	6.3	1790
32BS					10		23.0	6.8	1758
40BN			40.0	43	0		17.0	7.1	1752
40BS					10		18.0	6.4	1738
32CS	HAL-C	0.44	32.0	41			20.5	7.0	1925
40CN			40.0	43	0		17.0	6.4	1928
40CS					10		18.5	5.9	1922
22LpS	AL-1	26.2	21.9	38		150	24.0	5.8	1973
32LpN			32.0	41	0	160	23.0	5.0	1959
40LdN		0.0	40.0	43			9.0	4.7	1810

* W/(C+SF), s/a, and SF/(C+SF) indicate values of water-to-cementitious-binder ratio, sand-aggregate ratio, and replacement of cement by silica fume, respectively.

(2) Experimental Procedure

In order to investigate the physical properties of HAL aggregate and whether or not the targeted pore structure was obtained, HAL aggregates were tested for bulk specific gravity; 24-hour absorption (JIS A 1135); absolute specific gravity (JIS R 2205); total porosity of the aggregate particles; crushing value (British Standard. B.S. 812); formation of pores (observed by scanning electron microscopy); absorption under water pressure; and distribution of pore radius and pore volume (estimated by mercury intrusion). Absorption tests on the aggregate under water pressure were conducted by using the pressure vessel shown in Photo. 1. Absolutely dry aggregate was placed in the pressure vessel, and the water pressure increased to 4.9 MPa in steps of 0.98 MPa. Absorption was calculated by following the water drop in two measuring pipettes. Total porosity was evaluated as the ratio of total pore volume to bulk volume of aggregate particles, as shown in Equation (1). The occupancy ratio of open pore volume to total pore volume was also calculated from Equation (2), assuming that the maximum water pressure of 4.9 MPa brought about saturated absorption.

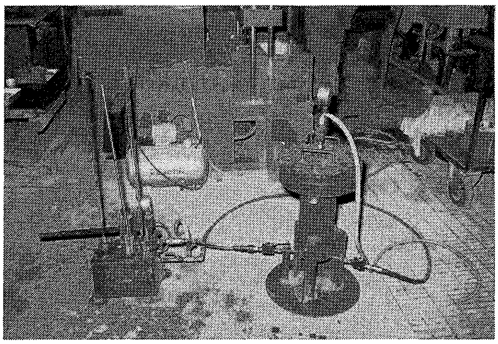


Photo. 1 Apparatus for water pressure absorption tests

$$\alpha = (1 - Dd/Da) \times 100 \ (\%) \quad (1)$$

$$\beta = (Qs \cdot Dd/\alpha) \times 100 \ (\%) \quad (2)$$

where:

α = total porosity of aggregate particles (%),
Dd = specific gravity of aggregate under oven-dry conditions,
Da = absolute specific gravity of aggregate,
β = occupancy ratio of open pore volume to total pore volume (%),
Qs = saturated absorption of aggregate (%).

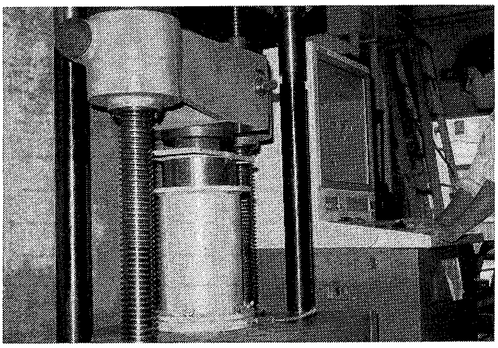


Photo. 2 Pressurizing of fresh concrete

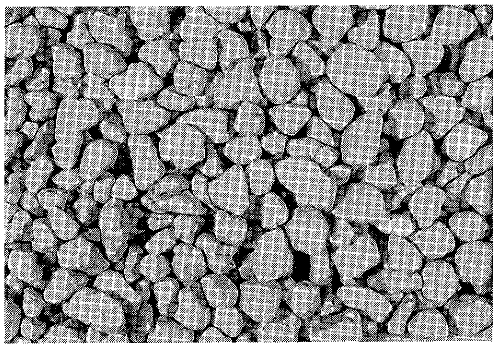


Photo. 3 Appearance of high-performance lightweight aggregate (HAL-B)

Tests for concrete compressive strength (JIS A 1108 and 1132) and resistance to freezing and thawing were conducted. Specimens for freezing and thawing tests were made as follows. After mixing, concrete was placed in the cylindrical steel container (ø20 × 36cm) to a height of 32cm, and then loaded in a testing machine up to a maximum load of 4.9 MPa at a rate of 1.96 MPa/min, as shown in Photo. 2. The concrete was removed from the container after being unloaded, and then cast into molds with the dimensions of 10×10×40cm. The molds were removed next day and cured in water to the age of 14 days. This process simulates the effects of pumping on resistance to freezing and thawing. Freezing and thawing tests were performed in accordance with ASTM C 666, Procedure A (Rapid Freezing and Thawing in Water). The freeze-thaw durability of the concrete was evaluated by measuring the relative dynamic modulus of elasticity, using a dynamic testing apparatus and the change in weight of the specimen. A durability factor was determined as given by Equation (3).

$$DF = P \cdot N / M \qquad (3)$$

where:

DF = durability factor of specimen,
P = relative dynamic modulus of elasticity after N cycles of freezing and thawing (%),
N = number of cycles until P reaches the specified minimum value (60%) or the specified number of cycles at which test is terminated (300 cycles), whichever is less,
M = specified number of cycles at which test is terminated (300 cycles).

The resistance of lightweight aggregates themselves to freezing and thawing was also examined by the following test method. Several lightweight aggregates (HAL-A, B, C and AL-1) were placed in an oven and heated until oven dry. Equal bulk volumes of each were used in freezing and thawing tests corresponding to ASTM C 666, Procedure A. The freeze-thaw durability of each aggregate was estimated by both changes in absorption and weight.

4. TEST RESULTS AND DISCUSSION

(1) Physical Properties of Aggregate

The appearance of the manufactured high-performance lightweight aggregate (HAL) is shown in Photo. 3. The color of this aggregate is gray-white and there are no cracks nor voids on the aggregate surface aside from a few minute voids.

The results of fundamental property tests are given in Table 3 and Fig. 3. The total porosity of HAL-A, B, and C aggregates was 62, 49, and 31 percent, respectively, and HAL-B had almost the same total porosity as conventional AL-1 and AL-2 aggregates. The absorption of HAL-A, B, and C aggregates under 4.9 MPa water pressure was as low as 3.24, 0.73, and 0.40 percent, or approximately 1/9 to 1/80 that of AL-1 and AL-2 aggregates. Furthermore, HAL aggregate particles returned very little water after the release of water pressure, while AL-1 and AL-2 aggregate particles returned a large amount, decreasing by

Table 3 Fundamental property test results of lightweight aggregate

Properties \ Type of aggregate	High-performance lightweight aggregate			Conventional lightweight aggregate	
	HAL-A	HAL-B	HAL-C	AL-1	AL-2
Specific gravity (oven-dry)	0.92	1.22	1.66	1.31	1.26
Absolute specific gravity	2.41			2.51	2.57
Total porosity of aggregate particles (%)	62	49	31	48	51
Absorption under 4.9MPa water pressure (%)	3.24	0.73	0.40	28.5	33.2
Occupancy ratio of open pore volume to total pore volume (%)	4.8	1.8	2.1	78	82
B.S. crushing value (%) [10% crushing value (kN)]	35.7 (127)	28.6 (158)	25.4 (197)	36.3 (82)	35.4 (110)

approximately 17 to 20 percent. These results give the occupancy ratio of open pore volume to total pore volume as 4.8 for HAL-A, 1.8 for HAL-B, and 2.1 percent for HAL-C, respectively. These values are quite small when compared with those of AL-1 and AL-2, which are 78 and 82 percent, respectively, and are equivalent to values obtained in past research [2]. The B.S. crushing values of HAL aggregates are smaller, while 10 percent crushing values are larger, than those of AL-1 and AL-2. This demonstrates HAL aggregates have improved strength, with even HAL-A - which has the largest total porosity - possessing the same strength or greater strength than AL-1 and AL-2. The strength of lightweight aggregate itself is thought to depend on the size and distributions of pores in the aggregate particles.

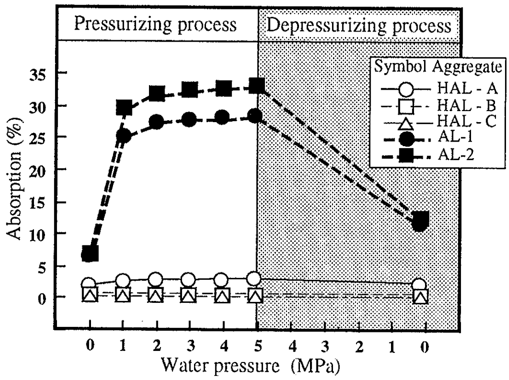
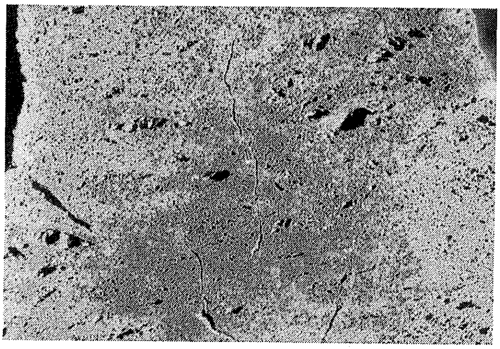


Fig. 3 Absorption test results under water pressure

Cross sections of the lightweight aggregates were observed at 10× magnification using a microscope, as shown in Photo. 4. HAL aggregates have almost no large voids or cracks, unlike the conventional lightweight aggregates, and the small-diameter pores are uniformly distributed. Furthermore, there is no difference in the state of pores among the aggregate particles. On the other hand, AL-1 aggregate had large voids and cracks of 1 to 3 mm, and there was some evidence of variations in pore state among AL-1 aggregate particles.

The pore structure of the aggregates, observed by SEM at 400× magnification, are shown in Photo. 5. With



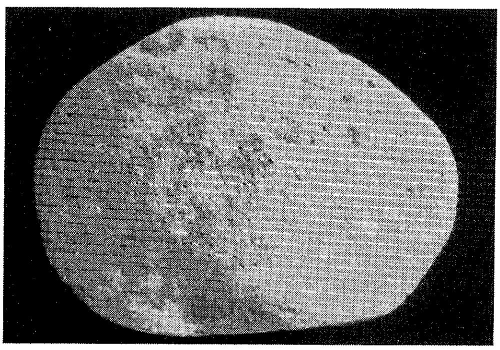


Photo. 4 Cross sections of aggregates (left : AL-1; right : HAL-B)

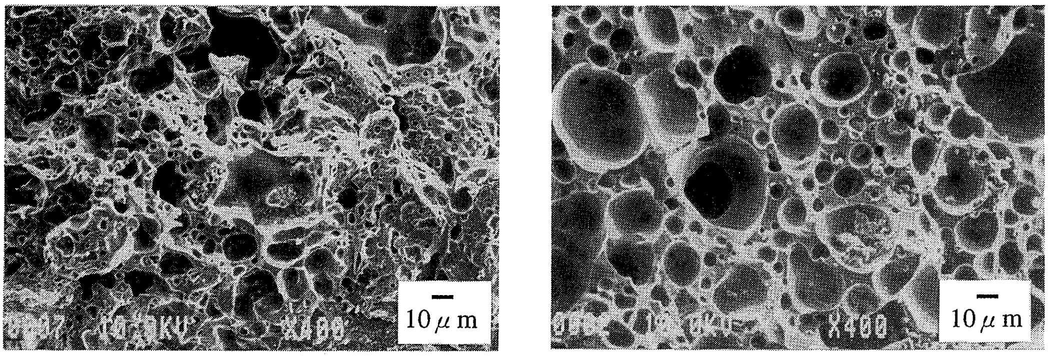


Photo. 5 Pore structure of aggregates observed by scanning electron microscopy (SEM)
(left : AL-2; right : HAL-B)

HAL-A, B, and C aggregates, the smaller the total porosity, the smaller the maximum diameter of the pores; the maximum diameters were approximately 150, 100, and 50 μm, respectively. HAL-A, B, and C aggregates had particularly large numbers of spherical pores of diameter were 2 to 50, 2 to 40, and 2 to 20 μm, respectively. On the other hand, conventional lightweight aggregates had large numbers of pores of 2 to 100 μm in diameter, though there were large voids of 1 to 3 mm, as mentioned above. The pores of AL-2 aggregate were irregular in shape, frequently adjoining the shells of other pores, and in some aggregate particles the pores were in a reticular network. According to SEM observations at 10,000×, pores with diameters less than several hundred nm were present in all aggregate types, though they were very small in number.

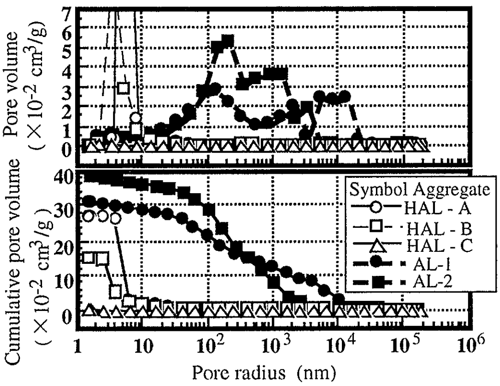


Fig. 4 Mercury intrusion test results

The results of the mercury intrusion tests are shown in Fig. 4. With AL-1 and AL-2 aggregates, estimates of pore radius were widely distributed, and pores of radius 100 to 200 nm were large in number. On the other hand, with HAL aggregates, hardly any mercury intruded until the pressure was increased to approximately 130 MPa, corresponding to the pressure at which mercury could intrude into pores with 5 nm or greater radii. The cumulative pore volume increased abruptly when the mercury pressure rose above 130 MPa. Since the pore structure of HAL aggregate, which is almost closed or isolated, collapses under high pressure, the amount of mercury intrusion should increase. Thus, the pore radii estimated in this test seem to be inconsistent with the SEM observations.

These test results indicate that we were able to manufacture high-performance artificial lightweight aggregate with small, closed pores in a uniform distribution. Using this aggregate, casting of the resulting concrete by pump is possible, even if dry aggregate is used. Moreover, no prewetting or presoaking process is necessary for concrete mixing and casting.

(2) Compressive Strength of Concrete

The compressive strength of lightweight concrete using HAL aggregates and AL-1 aggregate at the age of 28 days is shown in Fig. 5. When a lightweight aggregate is used to make high-strength concrete, little increase in compressive strength at the high-strength level is exhibited even if the water-to-cementitious-binder ratio (W/(C+SF)) is reduced. This is because the strength of the aggregate itself becomes the governing factor. In this situation, lightweight aggregate of higher specific gravity may be used to secure greater strength, though lightness is sacrificed to some extent. However, in these test results, when the

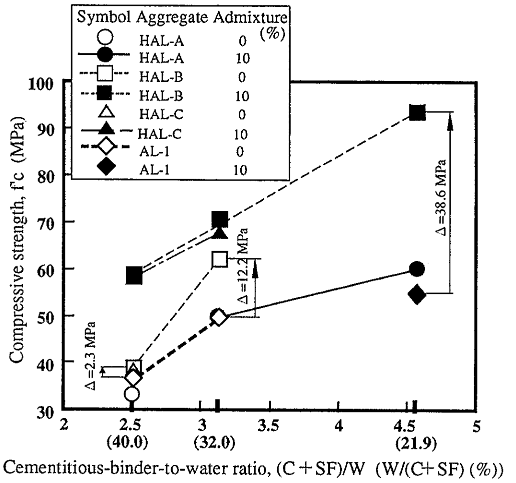


Fig. 5 Compressive strength at 28 days

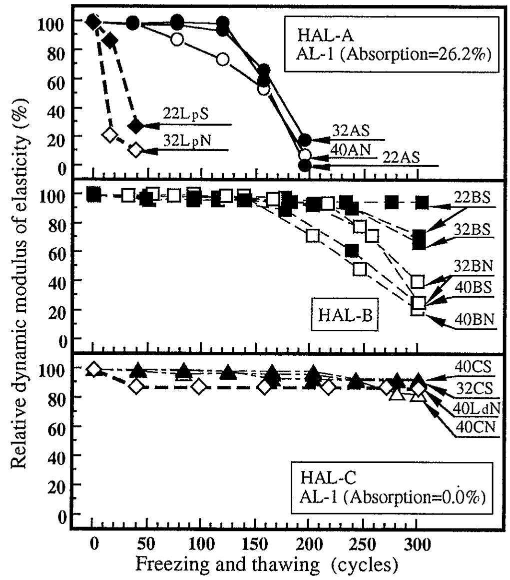


Fig. 6 Changes in relative dynamic modulus of elasticity due to freezing and thawing

water-to-cementitious-binder ratio is in the range 21.9 to 40.0 percent, even concrete containing the lightest HAL-A aggregate has almost the same compressive strength as lightweight concrete using AL-1 aggregate. With HAL-B aggregate, whose specific gravity and total porosity are nearly equivalent to those of AL-1 aggregate, the strength development of concrete was improved by 2.3 to 38.6 MPa in comparison with AL-1 concrete. This strength gain became clearer at lower W/(C+SF). Good correlation was noted between compressive strength and cementitious-binder-to-water ratio, and significant increase in compressive strength at the high-strength level can be expected if HAL-B aggregate is used, although AL-1 and HAL-A aggregate concretes had little increase in compressive strength when W/(C+SF) was between 21.9 and 32.0 percent.

These test results demonstrate that compressive strength at the high-strength level can be improved by using a high-performance artificial lightweight aggregate with small, closed pores distributed uniformly in the aggregate particles. According to other research by the authors [3], a compressive strength higher than 130 MPa can be obtained by adopting HAL-C grade aggregate and selecting an appropriate mix proportion. The splitting tensile strength and modulus of elasticity of HAL aggregate concretes, omitted in this paper, were also examined. Values were smaller in comparison with those of normal weight concrete, a fact pointed out by the authors and other researchers [3],[4].

(3) Resistance to Freezing and Thawing of Concrete

Tests of resistance to freezing and thawing were carried out on concretes using high-performance lightweight aggregates (HAL) and a conventional lightweight aggregate (AL-1). The properties of the fresh HAL concrete, which was pressurized in order to simulate pumping, were as follows. The air content was in the range of 3.1 to 4.8 percent, 1 to 3.5 percent lower than the post-mixing air content. Hardly any slump loss was noted, because little absorption by the aggregate was expected.

Figure 6 shows change in relative dynamic moduli of elasticity of the specimens after freezing and thawing. Concretes using prewetted AL-1 aggregate deteriorated dramatically, even with a water-to-cementitious-binder ratio of 21.9 percent (mixture 22LpS), and the relative dynamic modulus of elasticity fell to 28.3 percent after 39 cycles of freezing and thawing. On the other hand, in the case of concretes using HAL aggregates, even the concrete named 40AN - whose relative dynamic modulus of elasticity fell most quickly at an early stage of testing - had a relative dynamic modulus of elasticity of 73.1 percent after 119 cycles. Thus the fall in relative dynamic modulus of elasticity can be reduced by using HAL aggregate in lieu of prewetted AL-1 aggregate. The type of HAL aggregate and the water-to-cementitious-binder ratio (W/(C+SF)) also influenced the freeze-thaw resistance of HAL concrete. The lower the value of W/

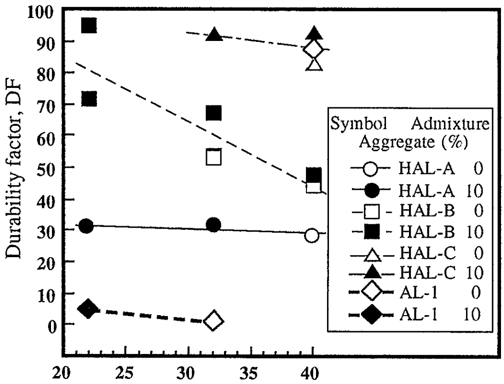


Fig. 7 Durability factor vs. W/(C+SF)

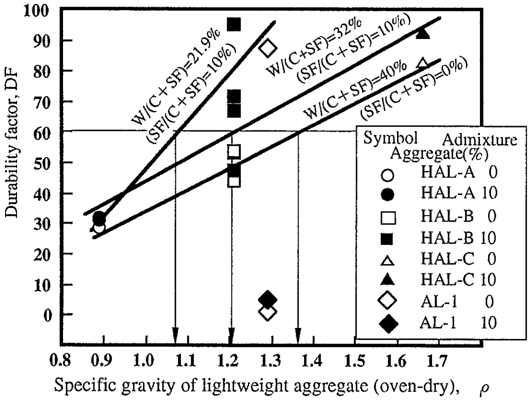


Fig. 8 Durability factor vs. specific gravity of aggregate

(C+SF) or the larger the specific gravity of the HAL aggregate, the smaller the reduction in relative dynamic modulus of elasticity became. The freeze-thaw resistance of concrete incorporating silica fume tended to be slightly higher than that of concrete without silica fume.

The relationship between durability factor and water-to-cementitious-binder ratio (W/(C+SF)) is illustrated in Fig. 7. It seems that there is no correlation between them. According to a linear regression analysis of each type of aggregate, however, a certain correlation is found. In the case of HAL-B aggregate, the durability factor of 45 rose as high as 95 as W/(C+SF) was reduced from 40.0 to 21.9 percent. On the other hand, in the case of concrete using HAL-A or C aggregate, the result was different. With HAL-A concrete, the durability factor fell to approximately 30 in all cases, regardless of W/(C+SF). Conversely, with HAL-C concrete, the durability factor was better than 80 in all cases. Thus, the properties of the HAL aggregate itself have a significant influence on the freeze-thaw resistance of the concrete incorporating them, though W/(C+SF) has same effect as pointed out in past research [5],[6].

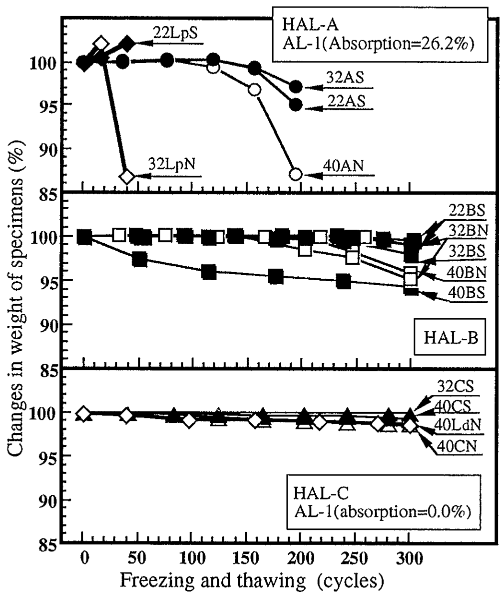


Fig. 9 Changes in weight of specimens subjected to freezing and thawing

Figure 8 shows the relationship between durability factor and oven-dry specific gravity of the HAL aggregate. The durability factor increases as the oven-dry specific gravity of the aggregate becomes higher, in the order A, B, and C. According to a linear regression analysis at a particular W/(C+SF), there is good correlation. It turns out that the oven-dry specific gravity of the HAL aggregate needs to be greater than a certain value in order to ensure superior durability. For example, if a durability factor higher than 60 is required, HAL aggregates with values of specific gravity greater than 1.07, 1.20, and 1.36 should be employed for concretes with W/(C+SF) values of 21.9, 32.0, and 40.0 percent, respectively. In order to ensure high durability for any value of W/(C+SF), it is advisable to use an aggregate with a specific gravity of 1.5 to 1.7 (HAL-C grade).

Figure 9 shows change in weight of specimens subjected to freezing and thawing. The weight loss of HAL concretes becomes smaller as W/(C+SF) falls or the specific gravity of the aggregate is increased. The weight loss of concrete using HAL-A aggregate was 1 to 2 percent of the initial specimen weight when the relative dynamic modulus of elasticity reached 60 percent. With further freezing and thawing cycles, the reduction in weight became more prominent and all specimens collapsed before reaching 300 cycles. With concrete using HAL-B aggregate, the weight of the specimen decreased by 0.4 to 5.7 percent at the end of the freezing and thawing test (300 cycles). With HAL-C aggregate, however, the reduction in weight was notably smaller, in the range 0.2 to 1.4 percent. Concrete weight loss due to freezing and thawing is generally caused by mortar scaling, aggregate pop-out, and spalling. In the case of normal weight concrete with a relatively high water-to-cement ratio, the main loss is through scaling. With lightweight concrete, it may be caused by pop-out as well as scaling. On the other hand, in the case of HAL concrete with a relatively low water-to-cementitious-binder ratio, it may result from pop-out and spalling, as shown in Photo. 6. Little pop-out or spalling occurred with HAL-C concrete and with concrete using absolutely dry conventional aggregate (mixture 40LdN). However, HAL-A aggregate concrete suffered from significant pop-out and spalling. It also appears that this pop-out and spalling is particularly prominent on the top placement surface, where the aggregate surface is more likely to be exposed by scaling. Hence the deterioration of HAL aggregate concrete due to freezing and thawing can be explained as below.

First, it is assumed that superior durability can always be obtained with HAL concrete because of the characteristics of the aggregate, whose pores are almost closed. Concrete using HAL aggregate with a low specific gravity (that is, a large total porosity), however, does not necessarily have superior durability. Pore diameters are large and the mutual separation between pores is small in such HAL aggregates. In this case, initial cracks on the aggregate surface occur when the surface pores become saturated and the expansive stress of freezing exceeds the strength of the pore partitions. The resulting cracks then propagate into the mortar and within the aggregate particles, forming continuous cracks. The closed state of the pores in the aggregate particles fails to be sustained. The result is deterioration of the HAL aggregate concrete.

The results given above lead us to a number of conclusions. The freeze-thaw resistance of lightweight concrete can be greatly improved by using a high-performance lightweight aggregate instead of a prewetted conventional lightweight aggregate. There is good correlation between freeze-thaw resistance of concrete using high-performance lightweight aggregate and the oven-dry specific gravity of the aggregate. The greater the specific gravity of the aggregate, the better the freeze-thaw durability obtained.

(4) Mechanism of Freeze-Thaw Deterioration of High-Performance Lightweight Concrete

In order to clarify the mechanism of HAL concrete deterioration due to freezing and thawing, two additional tests were conducted. The results are shown in Figs. 10 to 12.

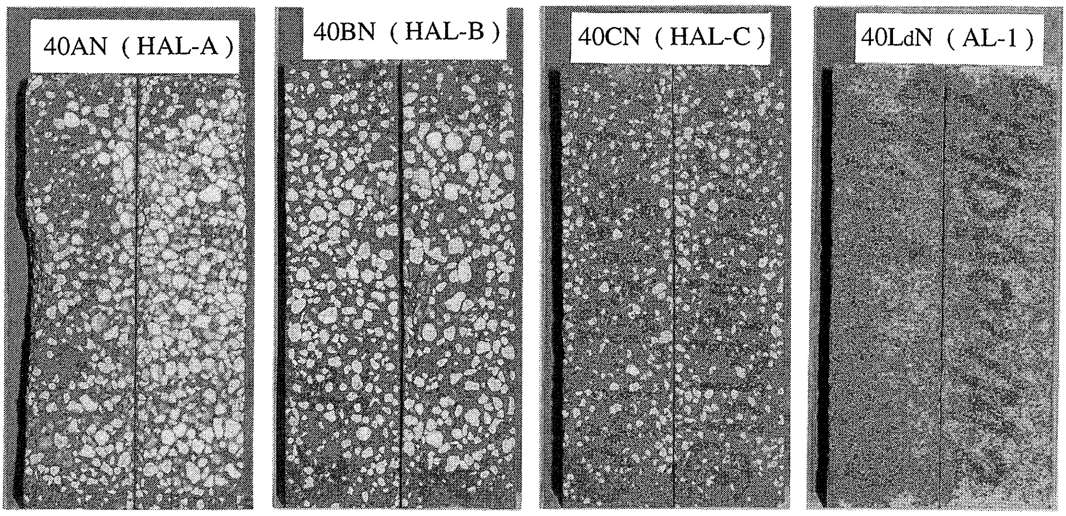


Photo. 6 Specimens after freezing and thawing tests

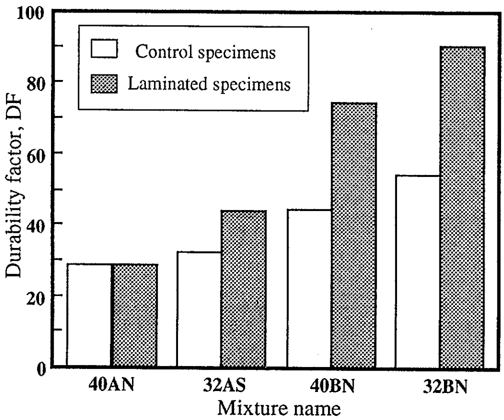


Fig. 10 Freezing and thawing test results

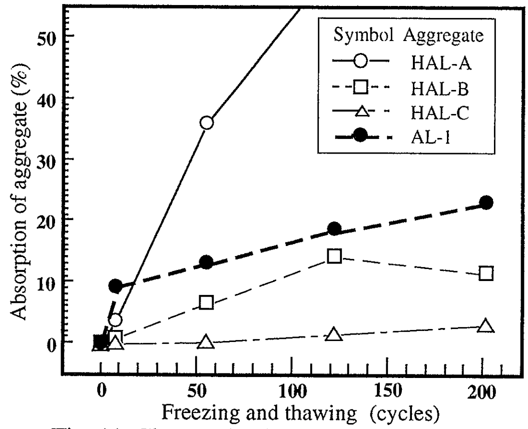


Fig. 11 Changes in absorption of aggregates subjected to freezing and thawing

Figure 10 shows freezing and thawing test results for HAL concrete. In this experiment, the top layer of the specimens was replaced by mortar sieved from the freshly mixed concrete. This was done to examine the effect of protecting this top layer. Since HAL aggregate near the top placement surface is likely to be exposed to water, the top placement surface is more likely to be damaged by pop-out and spalling. With these specimens (laminated specimens), better durability was achieved in comparison with the conventional specimens (control specimens). Of particular note is the case of HAL-B concrete, where durability factors of 74.5 and 90.4 were achieved for laminated specimens with W/(C+SF) values of 40.0 and 32.0 percent, respectively. The weight loss of these specimens was also smaller. Furthermore, the laminated specimens showed almost no deterioration on the top placement surface. However, deterioration occurred where the aggregate was near other surfaces of the specimens. It is reasonable to say that durability results depend on whether there is sufficient water around the HAL aggregate surface or not.

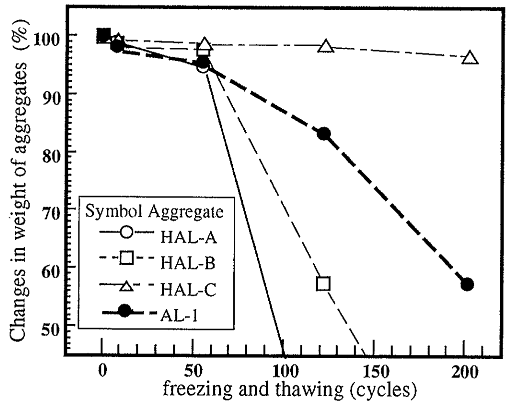


Fig. 12 Changes in weight of aggregates subjected to freezing and thawing

Figures 11 and 12 show changes in absorption and weight of the HAL aggregate itself due to freezing and thawing action in water. Absorption rose as the number of freezing and thawing cycles increased, although the pores in the closed state were entrained. The absorption reached 36.1 percent after 55 cycles in the case of HAL-A. Also the weight of oven-dry HAL-A and B aggregates decreased considerably with repetitions of the freezing and thawing cycle. The greater the specific gravity of an HAL aggregate, the smaller the recorded weight loss and also the lower the absorption. With HAL-C aggregate, an increase in absorption of approximately 3 percent and a decrease in weight by approximately 3 percent were recognized after 201 cycles, at which point the test was terminated. These changes are very small. These test results verify that HAL aggregate concrete deteriorates due to pop-out and spalling when continuous cracks occur in the aggregate particles and mortar, and when the closed state of the pores cannot be sustained. With respect to conventional lightweight aggregates, past research shows that the aggregate itself suffers little damage, and is very durable [7]. In this study, however, a large increase in absorption and a large decrease in weight were observed for the conventional lightweight aggregate (AL-1), and the aggregate was damaged in the same way as HAL-A and B aggregates. This difference in results is thought to be a consequence of different test methods and the number of freezing and thawing cycles.

If HAL aggregate concrete is employed in cold regions, certain considerations may be necessary. It has been said that the test method corresponding to ASTM C 666 Procedure A is too severe for the freeze-thaw durability evaluation of actual concrete members. Few concrete members are subjected to the severe exposure conditions specified by this method. The outer walls of oil platforms operating in the Arctic Ocean are likely to be exposed to these conditions, and in such cases we recommend that HAL-B or C aggregate (oven-dry specific gravity of approximately 1.2 or 1.6) should be chosen, depending on W/(C+SF) in order to assure sufficient durability. On the other hand, most conventional structures are exposed to much milder conditions, and superior durability can be assured by using HAL-B grade aggregate. According to the past studies, adequate durability is reportedly obtained by using prewetted conventional lightweight aggregate, as long as exposure conditions are not too intense [7],[8]. Therefore, adequate durability can in practice be obtained even if HAL-A aggregate (oven-dry specific gravity of approximately 0.9) is used.

On the basis of this discussion, we can say that high-performance lightweight aggregate concrete deteriorates due to pop-out and spalling when an aggregate with a low specific gravity is used, since the closed state of the pores in the aggregate particles cannot be sustained. However, even if a high-performance lightweight aggregate of low specific gravity is used, adequate durability can be assured by taking into account both exposure conditions and the mix proportion.

5. CONCLUSIONS

A high-performance artificial lightweight aggregate has been developed through application of a new manufacturing method. The performance of this aggregate itself and the properties of the resulting concrete have been examined. The results obtained are summarized below.

(1) A high-performance artificial lightweight aggregate can be obtained by selecting a suitable raw material and adopting a new manufacturing method. This aggregate has small, almost-closed pores distributed uniformly in the aggregate particles. No prewetting or presoaking process is necessary, and concrete made with this aggregate can be cast by pump, even if the aggregate is used dry, since no absorption occurs under water pressure.

(2) The high-performance lightweight aggregate is itself stronger than conventional lightweight aggregate because of the difference in pore structure. The low increase in compressive strength noted in lightweight concretes at the high-strength level is improved, ensuring lightweight concrete with higher compressive strength.

(3) The freeze-thaw resistance of high-performance lightweight aggregate concrete is significantly improved in comparison with that of concrete using sufficiently prewetted conventional lightweight aggregate, even though the high-performance lightweight aggregate concrete may be pumped.

(4) There is a good correlation between freeze-thaw resistance of concrete using this new aggregate and the oven-dry specific gravity of the aggregate. The greater the specific gravity of the aggregate, the higher the freeze-thaw durability becomes. Extremely high durability can be obtained by using an aggregate with a specific gravity of approximately 1.5 to 1.7, regardless of the mix proportion (e.g., water-to-cementitious-binder ratio).

(5) Deterioration due to freezing and thawing occurs when the closed state of the pores in the aggregate particles cannot be sustained.

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